7000-7

(4)

Non-Steady Combustion of Composite Solid Propellants

Annual Research Progress Report

N.S. Cohen
L.D. Strand

April 1982

Prepared for
U.S. Air Force Office of Scientific Research
Through an agreement with
National Aeronautics and Space Administration
by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

UNCALSSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 82-0654	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) NON-STEADY COMBUSTION OF COMPOSITE SOLID PROPELLANTS		5. TYPE OF REPORT & PERIOD COVERED ANNUAL 1 Oct 80 - 31 Dec 81
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) N S COHEN L D STRAND		8. CONTRACT OR GRANT NUMBER(s) AFOSR-ISSA-81-00019
9. PERFORMING ORGANIZATION NAME AND ADDRESS CALIFORNIA INSTITUTE OF TECHNOLOGY JET PROPULSION LABORATORY 4800 OAK GROVE DR, PASADENA, CA 91109		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2308/A1
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BOLLING AFB, DC 20332		12. REPORT DATE April 1982
		13. NUMBER OF PAGES 27
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

SOLID PROPELLANT COMBUSTION MODELING
COMBUSTION INSTABILITY

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An analytical model for the pressure-coupled combustion response function was developed. The unique feature of this model is that it accounts for effects of ammonium perchlorate (AP) size distribution (composite propellant heterogeneity) in terms of a preferred frequency mechanism based on periodic fluctuations in the propellant formulation. Properties of the response function have been calculated theoretically over a range of the governing variables. The dependence of burn rate on AP concentration is found to be an important new combustion parameter in this context. Progress has been made in devising experimental

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

methods to characterize the heterogeneity of propellants in terms of fluctuations in the formulation and dynamic burning at constant pressure. Continued work is needed to perfect these methods and relate the results to response function behavior.

ACKNOWLEDGEMENT OF GOVERNMENT RIGHTS AND SPONSORSHIP

Research was sponsored by the Air Force Office of Scientific Research, Air Force Systems Command, USAF, under Contract AFOSR ISSA-81-00019, through an agreement with the National Aeronautics and Space Administration, NASA 7-100, Task Order RD-182, Amendment No. 132. The United States Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon.

CONTENTS

Figures

Tables

SECTION 1

RESEARCH OBJECTIVES

1.1 OVERALL OBJECTIVE

The objective of this research program is to develop an understanding of oxidizer particle size effects on the non-steady combustion behavior of composite solid propellants. This understanding is expressed by the development of suitable analytical models to describe known or experimentally observed phenomena. A combination of theoretical and experimental tasks is performed toward the accomplishment of this objective. Results are disseminated by technical presentations and publications, and through a variety of interchange functions with government laboratories and contractors.

1.2 SPECIFIC OBJECTIVES FOR FISCAL YEAR 1981

Particular attention has been given to the problem of combustion instability which is promoted by the development of improved rocket motor capabilities for future missile systems. High pressure combustion and deflagration-detonation transition (DDT) are of interest in the development of improved armament and advanced high energy rocket propellants. The specific objectives are listed as follows:

(1) Develop an analytical model for the pressure-coupled response function accounting for effects of composite propellant heterogeneity.

(2) Develop experimental methods to characterize the heterogeneity of composite propellants for diagnostic purposes, and to complement the analytical model.

(3) Acquire a data base on the high pressure combustion behavior of composite solid propellants using the closed vessel apparatus installed in FY 1980.

(4) Evaluate the feasibility of constructing an improved DDT model by combining the Stanford Research Institute (SRI) shock hydrodynamics model with the JPL transient combustion model.

A literature survey on analytical response function models, which account for oxidizer particle size effects (i.e., heterogeneity), was completed during FY 1980. Based on the review (Ref. 1), an analytical model was formulated conceptually. The work planned for FY 1981 consisted of completion of the analytical modeling and whatever computer programming would be required, and acquiring solutions over a range of the governing variables to determine the properties of the response function. Demands of future propulsion systems and the viability of combustion tailoring through control of oxidizer particle size distribution, make it imperative that the effects of size distribution be understood (Ref. 2).

Three types of experiments were considered to characterize the heterogeneity of composite propellants and its effects on combustion behavior. The first experiment, which is non-destructive, is to perform energy dispersive analysis of x-rays (EDAX) scans of propellant samples, and Fourier decompositions of the measured fluctuations in chlorine intensities representative of local ammonium perchlorate (AP) concentrations. The second experiment is to use the JPL microwave burner (Ref. 3) to measure dynamic burning rates at constant pressure, and to analyze the data for frequency components. The third experiment is to use the burner to measure response functions. It is desired to seek evidence of consistent preferred frequency behavior, and to relate the observed frequencies to the heterogeneity of real propellants.

The closed vessel apparatus was to be used to obtain burning rate and surface structure data for composite propellants over the pressure range 1-7 kbar (100-700 MPa). This would extend our state of knowledge of combustion behavior to higher pressures and conditions approaching DDT. A serious deficiency of high pressure combustion and DDT analysis has been the need to assume the nature of the combustion at high pressures.

A suitable model for the shock hydrodynamics of DDT has been developed by Cowperthwaite (Ref. 4). Like other models of this type, however, it uses a simple burn rate law to describe the mass and energy generation due to combustion. A transient combustion model for application to the DDT problem was developed at JPL in FY 1978 (Ref. 5). Although this model is subject to uncertainties of high pressure combustion behavior, it was considered that by combining the two models, a good description of the DDT process would be provided.

SECTION 2

STATUS OF THE RESEARCH EFFORT

2.1 RESPONSE FUNCTION MODELING

A new analytical model was developed for the linear pressure-coupled response function. The new feature of this model is that it contains a mechanism by which the heterogeneity of composite propellants provides a direct contribution to the combustion driving.

2.1.1 Mechanism

It is hypothesized that the mechanism for the heterogeneity contribution arises from periodicities in the structure of a well-mixed composite propellant. The motion of any planar surface representing the burning front through this medium will evoke the periodicities at frequencies represented by:

$$f_j = \frac{r_o}{d_j} \quad (1)$$

where f_j = a characteristic frequency

r_o = mean burning rate

d_j = a characteristic dimension in the propellant, possibly the particle size or a feature related to particle size

The periodicities in the structure imply periodicities in the properties of the propellant which determine the burning rate. Thus, the "steady-state" burning rate, r_o, exists only as a time average. In real propellants, as opposed to idealized models of propellants, it can be expected that the fluctuations will have broad-band frequency content and diffuse amplitudes. It is assumed that the periodicities in a given property may be represented by:

$$h = h_o + \sum_j h_j e^{i\omega_j t} \quad (2)$$

where h = a given property; h_o is the mean value and h_j is the perturbation amplitude associated with the j^{Th} component

$i = \sqrt{-1}$

ω_j = angular characteristic frequency

t = time

Perturbations in h will contribute to the acoustic driving if they occur at the same frequency as the pressure oscillations. Considering the nature of real propellants, it is likely that some component of the heterogeneity will be present to contribute at any acoustic frequency. Then an overall combustion response can be defined as the sum of the classical response to the pressure perturbations (Ref. 6), plus a heterogeneity response contribution.

$$R_p = R_c + R_h \frac{h'/h_o}{p'/p_o} \tag{3}$$

where R_p = pressure-coupled response function, $\dfrac{m'/m_o}{p'/p_o}$

R_c = classical component for a homogeneous medium, $\left(\dfrac{m'/m_o}{p'/p_o}\right)_h$

R_h = heterogeneity component, at constant pressure, $\left(\dfrac{m'/m_o}{h'/h_o}\right)_p$

m = mass flux; m' is the fluctuating value
p = pressure; p' is the fluctuating value

The property of greatest interest is the propellant formulation represented by the oxidizer concentration, α. It is reasoned that the propellant formulation will fluctuate on the macroscopic scale during burning. Manifestations of such fluctuations have been observed experimentally (Refs. 7-9). These fluctuations, in turn, give rise to fluctuations in formulation-dependent combustion parameters which affect burning rate. The nature of such parameters will depend upon the particular combustion model used and any assumptions made.

2.1.2 Analysis

A perturbation analysis has been carried out utilizing the BDP model (Ref. 10) to represent the composite propellant combustion process. The analysis is similar to one published by Hamann (Ref. 11), except that perturbations in the formulation are considered, as well as perturbations in pressure. The analysis employs the following assumptions, in addition to the foregoing hypotheses:

- perturbation quantities are harmonic and small compared to mean values;
- for any frequency of pressure perturbations, there are perturbations in the formulation occurring at the same frequency;
- the solid propellant is semi-infinite and of uniform and constant thermal properties;

- the process is one-dimensional;

- the gas phase behaves in a quasi-steady manner.

It was determined that the components of the response function, R_c and R_h, may be expressed in a form derived by Zeldovich (Ref. 12).

$$\frac{R_c}{n_p} = \frac{1}{1 - \sigma_p(T_{w_o} - T_o)(1 - \frac{1}{\lambda}) + \sigma_T (\lambda-1)} \tag{4}$$

$$\frac{R_h}{n_\alpha} = \frac{1- \frac{K\rho}{n\alpha} \sigma_p(T_{w_o}-T_o)(1- \frac{1}{\lambda})}{1- \sigma_p (T_{w_o}-T_o)(1- \frac{1}{\lambda}) + \sigma_T (\lambda-1)} \tag{5}$$

where

n_p = pressure exponent, $\left(\frac{\partial \ln m}{\partial \ln p}\right)_{\alpha,\, T_o}$

σ_ρ = temperature sensitivity, $\left(\frac{\partial \ln m}{\partial T_o}\right)_{\alpha,p}$

T_{w_o} = mean surface temperature

T_o = initial bulk temperature of the propellant

λ = a complex quantity dependent upon oscillatory frequency (Ref.6)

$\sigma_T = \left(\frac{\partial T_w}{\partial T_o}\right)_{\alpha,p}$

n_α = concentration exponent, $\left(\frac{\partial \ln m}{\partial \ln \alpha}\right)_{p,\, T_o}$

$K\rho$ = dependence of propellant density on α, $\left(\frac{\partial \ln \rho}{\partial \ln \alpha}\right)_{p,\, T_o}$

It is interesting that the heterogeneity component and the classical component take on a similar form. The advantage of the Zeldovich method, as pointed out by Glick & Condon (Ref. 13), is that the response function can be expressed in terms of key steady-state combustion parameters (as shown above). Thus, a particular combustion model can be used to calculate these parameters, which is relatively easy. A perturbation analysis can be exceedingly tedious for the more complicated combustion models developed in recent years. Having validated the method for the BDP model, it was assumed that the method could

be used in association with the improved Cohen & Strand model (Ref. 14) to calculate these combustion parameters and thereby calculate the response function components.

2.1.3 Parametric Studies

The ranges of variables used to perform these computations are listed as follows:

P_0, mean pressure	1.4-15 MPa
T_0, propellant bulk temperature	230-340°K
α_0, mean AP weight fraction	0.73-0.92
D, AP particle size	0.7-400 microns

These ranges cover the conditions of interest. A broad range is used for α_0 to accommodate research propellants at the low end, and because interesting properties of $n\alpha$ were uncovered at the high end. The parameter n_α is a new parameter in combustion theory; neither theoretical calculations nor data bases have been published prior to this work. Because of the lack of prior information, a set of theoretical results is presented in Table 2-1. The magnitudes and variabilities are striking; pressure exponent does not exhibit anything near this kind of behavior. Moreover, the implication of instability suppression by the high negative values at high α_0 (past stoichiometric ratio) is most intriguing.

The resulting ranges of variables for the response function calculations are listed as follows:

$\sigma_p\ (T_{w_0}-T_0)$	0.3 - 1.5
$K_p/n\alpha$	-0.8 - 0.8
$\dfrac{\sigma_T}{\sigma_p(T_{w_0}-T_0)}$	0.033 - 0.092
Ω, dimensionless frequency	0 - 50

These ranges were derived from the combustion model calculations and acoustic frequencies of interest. Groupings of parameters follow Eqs. (4) and (5). The parameter σ_T is expressed as a proportion with $\sigma_p(T_{w_0}-T_0)$ because the calculations revealed a good correlation between them. These groupings serve to reduce the required latitude of the investigation.

Results are typified by the plots of the real part of R_c/n_p versus Ω, for various $\sigma_p(T_{w_0}-T_0)$, shown in Figure 2-1. It is observed that the peakedness of the response is very sensitive to the temperature parameter. The peak region becomes narrower as the magnitude of the peak increases, but the peak response frequency does not change very much. The behavior of R_h/n_α is very similar. Actually, in the limit of $K_p/n\alpha = 0$, the curves become identical to the corresponding R_c/n_p curves. As $K_p/n\alpha$ becomes more positive, the peak

Table 2-1. Calculated Values of the Concentration Exponent* Using the Cohen-Strand Model

Pressure (MPa) \ D(μm)	0.7	5	20	90	200	400
	α_0 = 0.73 (K_p = 0.618)					
1.4	8.1	8.2	8.3	4.1	3.6	3.8
3.4	8.4	8.6	5.4	2.8	3.7	4.6
6.8	8.9	9.4	4.4	3.0	4.7	6.0
14	9.3	5.8	3.1	4.8	6.2	7.2
	α_0 = 0.80 (K_p = 0.719)					
1.4	5.4	5.6	6.2	3.9	2.9	2.6
3.4	5.6	6.2.	7.1	3.2	2.9	3.2
6.8	5.7	6.8	4.2	3.0	3.5	4.8
14	6.0	7.5	3.4	3.6	5.0	6.9
	α_0 = 0.88 (K_p = 0.853)					
1.4	1.6	2.4	4.7	13.0	6.5	4.6
3.4	1.9	4.0	9.9	7.0	4.9	4.2
6.8	2.2	5.3	14.0	3.4	4.3	4.7
14	3.0	10.3	7.3	4.3	5.1	7.1
	α_0 = 0.92 (K_p = 0.928)					
1.4	-6.5	-23.1	-62.5	-23.9	-13.4	-10.6
3.4	-10.8	-47.8	-45.1	-16.3	-11.8	-14.8
6.8	-18.2	-71.9	-28.1	-12.1	-15.6	-30.0
14	-31.9	-45.2	-17.3	-16.6	-32.3	-59.4

* $n_\alpha = \left(\frac{\partial \ln r}{\partial \ln \alpha}\right)_{p,T_0} + K_p$

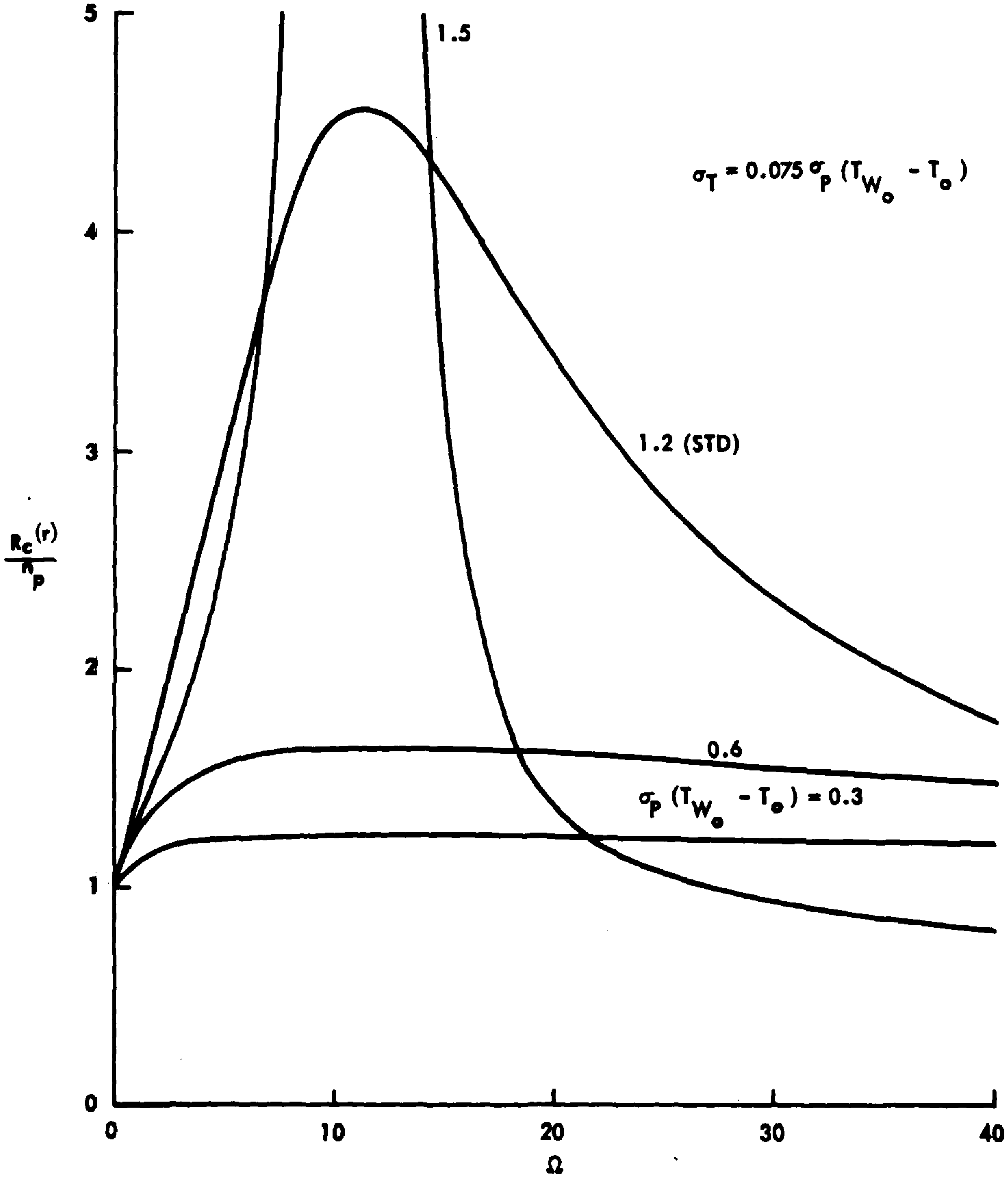

Figure 2-1. Effect of Temperature Sensitivity of Burn Rate on the R_c Component of the Combustion Response

response decreases and the peak region narrows. As it becomes more negative, the opposite occurs. Peak response frequency for R_h/n_α is not very sensitive to K_p/n_α. The effect of increasing the ratio $\sigma_T/(\sigma_p(T_{w_0}-T_0))$ is to decrease the peak magnitude, narrow the peak region, and decrease the peak response frequency for both R_c/n_p and R_h/n_α curves.

Response function component curves have been calculated for each of the Table 2-1 entry conditions. The results summarized below can be explained by the effects of the independent variables upon the key combustion parameters.

As a general trend, increasing pressure tends to increase the frequency at which the peak values of R_c and R_h occur. Increasing pressure also tends to increase the peak value of R_h. The effect of pressure on the peak value of R_c is particle-size dependent. For the finer sizes, the peak R_c decreases or goes through a minimum with increasing pressure. For the coarser sizes, the peak R_c increases or goes through a maximum with increasing pressure.

Increasing particle size tends to decrease the frequency at which the peak values of R_c and R_h occur. The peak value of R_h tends to maximize in the intermediate-coarse size-range. The behavior of R_c is more complicated. In general, peak values of R_c tend to a minimum at fine-intermediate sizes and to a maximum at intermediate-coarse sizes.

Increasing total solids tends to increase the frequency at which the peak values of R_c and R_h occur. The effect on the peak value of R_c is particle-size dependent. For fine-intermediate sizes, the peak R_c decreases or goes through a minimum with increasing total solids. For intermediate-coarse sizes, the peak R_c goes through a minimum or increases with increasing total solids. The effect on R_h is dominated by the sign change at stoichiometric ratio, beyond which the peak values become strongly negative. On the fuel-rich side, the peak R_h tends to increase with total solids.

Finally, increasing the propellant bulk temperature tends to decrease the peak response magnitudes and increase the peak response frequencies.

Combining the two response function components to determine the overall response, R_p, requires knowledge of the R_h multiplier in Eq. (3). This, in turn, requires knowledge of the heterogeneity (or formulation) perturbations and the pressure perturbations. These are subjects of experimental work in progress and further analysis planned for the future. In the meantime, it is assumed that the multiplier takes the form of the particle size distribution. Computations on this heuristic basis show N + 1 peaks in the response function curve, where N is the number of particle size modalities (the additional peak comes from the R_c component). Fewer than N + 1 peaks can appear, however, where two of the components resonate at comparable frequencies or where the relative contribution of a component is small. Thus, a peak can be masked by another peak or have a skewing effect on the appearance of a more dominant peak. Response function curves which seem to have unconventional shapes can be rationalized in this manner. The calculated curves tend to be dominated by the heterogeneity component(s) because n_α tends to be much larger than n_p. Thus, combinations of coarse AP and low burn-rate produce dominant

peaks at low frequencies, and combinations of fine AP and high burn-rate produce dominant peaks at high frequencies. These trends are correct in a broad qualitative sense, but more cannot be made of them until the nature of the heterogeneity of actual propellants is understood. At this stage of the work, the most significant finding is the potential importance of the combustion parameter n_α in causing instability.

2.1.4 Dissertations

A progress paper was presented at the 18th JANNAF Combustion Meeting (cited in Subsection 5.1). A more detailed peer review dissertation paper is currently in preparation for distribution at about the same time as this annual report. AIAA publications are planned in the future.

2.2 RESPONSE FUNCTION EXPERIMENTS

2.2.1 EDAX/SEM Studies

Progress was made in the development of an experimental method to characterize the heterogeneity of actual composite propellants. The method is based upon the fact that AP has chlorine atoms and binder does not. High magnification photographs of propellants obtained by EDAX, in association with a scanning electron microscope (SEM), present images in which AP appears as white particles and binder appears as black background or interstices. This is achieved by selecting chlorine as the element for the EDAX analysis. The photographic negative is then analyzed by means of a microdensitometer. The analyzer divides the negative into incremental areas consisting of the length and approximately 0.2% of the width. For each area or scan line, an integrated average gray level is measured. This average gray level is proportional to the AP concentration along that scan line. Fluctuations in the average gray level are measured as the microdensitometer proceeds from scan line to scan line. Results are presented in the form of average gray level versus distance and the dimensional frequency components of the fluctuations in the average gray level. The average gray level is related to AP content by calibrating both a white and black region.

Initial work was performed with the ideal geometry shown in Figure 2a. This geometry represents a unimodal propellant consisting of spherical particles in a closely-packed hexagonal array. The fluctuations in the average gray level are shown in Figure 2b, and the frequency components are shown in Figure 2c. The regularity in the fluctuations is as would be expected. Note that there is a multiplicity of frequency components. The first six, which are the largest, can be associated with the particle diameter, particle radius, and four dimensions which are characteristic of the interstitial spacings (radius multiplied by $(\sqrt{3}-1)$, $1/\sqrt{3}$, 1/2 and $(1-\sqrt{1/3})$). Thus it is erroneous to equate preferred frequency behavior to the particle size alone, even for an ideal geometry.

The analogy to the Figure 2 group, for an actual composite propellant, is shown in the Figure 3 group. The propellant is the JANNAF standard A-13 propellant, consisting of 76% AP (monomodal 61 micron, range from 5-150 microns). Figure 3a is the EDAX photograph, taken at a magnification of 50.

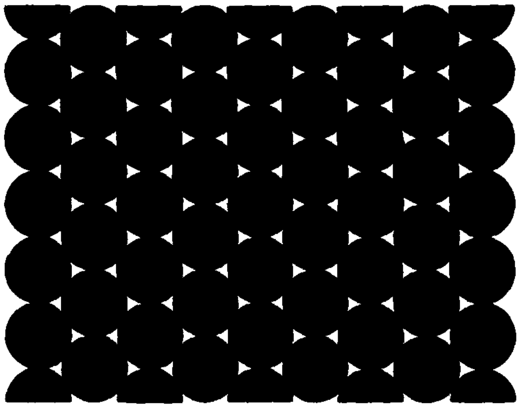

Figure 2a. Idealized Structure of Unimodal Composite Propellant

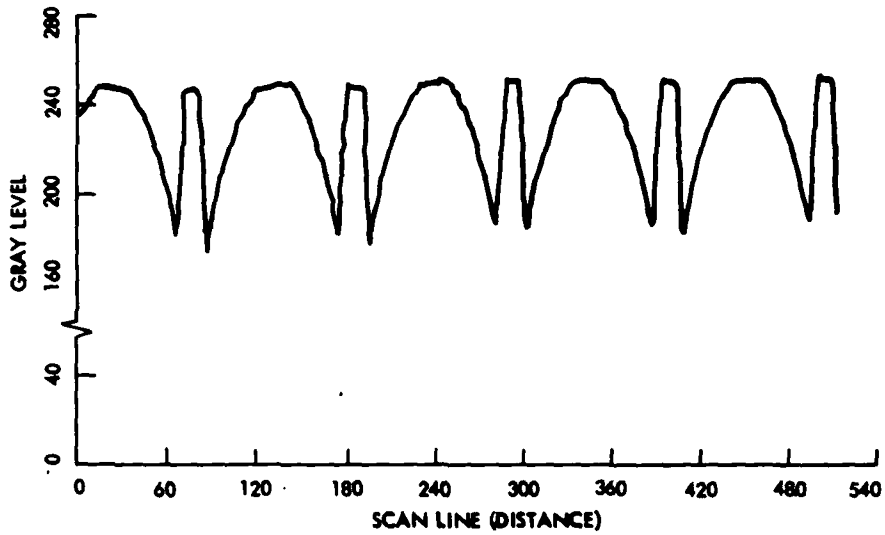

Figure 2b. Fluctuations in Average Gray Level Along Scan Lines

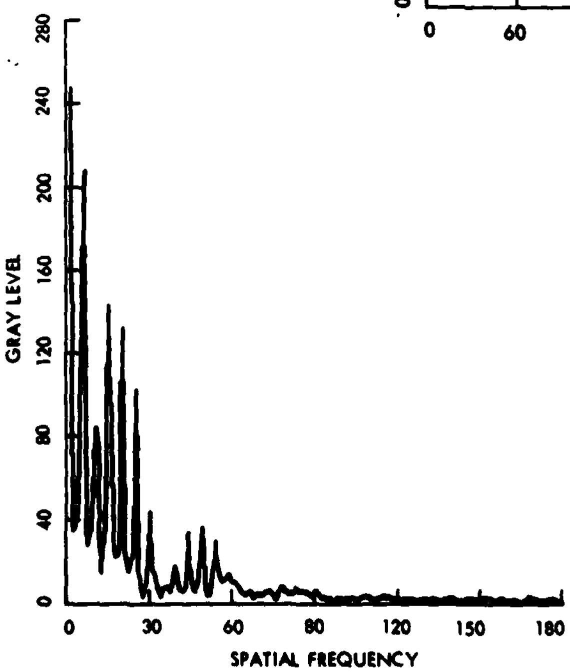

Figure 2c. Frequency Components of Scan Line Gray Level Averages

Figure 3a. SEM Photograph of A-13 Propellant, 50x

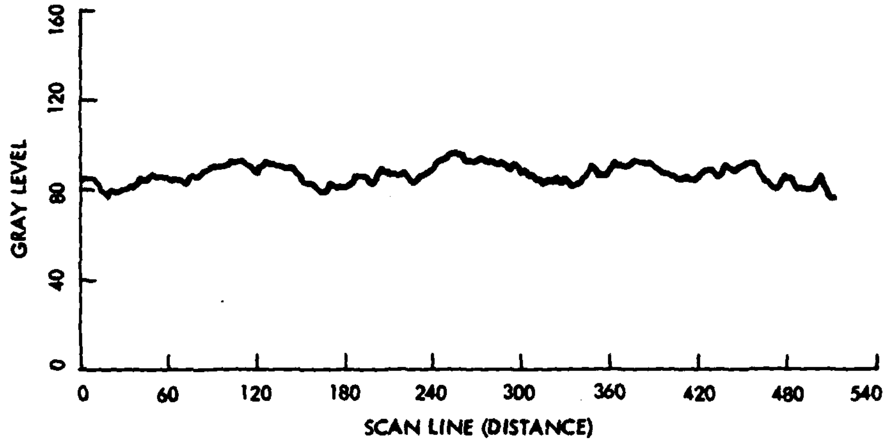

Figure 3b. Analysis of EDAX Chlorine Map - Fluctuations in Average Gray Level Along Scan Lines

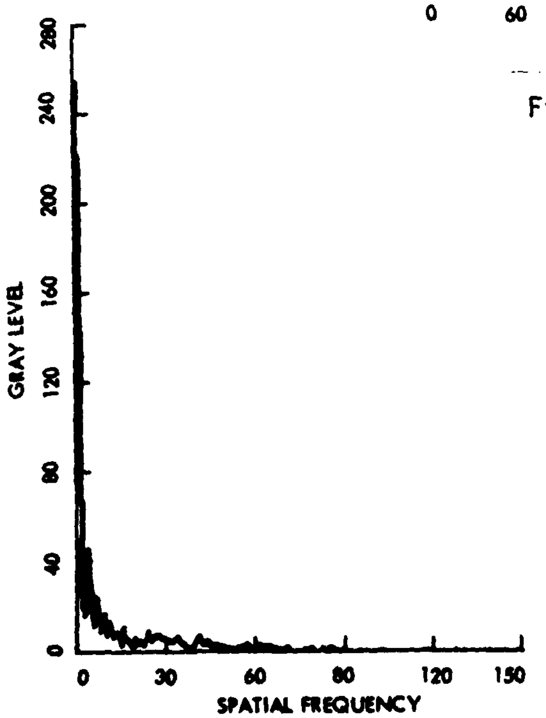

Figure 3c. Analysis of EDAX Chlorine Map - Frequency Components of Scan Line Gray Level Averages

At this magnification, the length is about 40 mean particle sizes and the densitometer scan line width is about 1/20 of a mean size. The magnifications (and number of photographs) required to characterize a propellant will depend upon the size distribution in order to achieve a statistical representation and adequate resolution. The fluctuations in Figure 3b are not as regular as in Figure 2b, which would be expected because of the sizes and shapes of particles in propellants. However, the amplitudes of the fluctuations in Figure 3b are surprisingly large. These correspond to fluctuations of ± 8.6 wt. percent AP. Many frequency components appear in Figure 3c. These frequencies correspond to dimensions ranging from 28-297 microns which are coarser than the actual range of particle sizes and do not include expected interstitial fine structure. The power of this spectrum is considerably less than that produced by the ideal geometry in Figure 2c, as would be expected. Varying the magnification confirmed the need to do so in order to pick up the propellant fine structure.

Future plans consist of implementing softwear to automate the data acquisitions, studying reproducibility as a function of propellant sample location, completing the characterization of A-13 propellant, and studying a series of selected propellants. At this stage of the work, it can be concluded that the formulation of a composite propellant does fluctuate on the macroscopic scale, and these fluctuations have significant amplitudes and considerable frequency content.

2.2.2 Dynamic Burning at Constant Pressure

The JPL microwave burner apparatus was used to measure dynamic burning rates at constant pressure. Ordinarily, this apparatus operates in association with an imposed pressure oscillation to measure the response function. For the present purpose, the pressure oscillation is not imposed. Testing at constant pressure provides the opportunity to measure the R_h component of the response function, assuming that the burning rate fluctuations are due to the heterogeneity. The other purpose of testing at constant pressure is to detect frequency components that could be related to the EDAX/SEM data and to peak response function frequencies. Tests were performed with several propellants, including A-13, at several pressures.

In general, the data show considerable frequency content with strongest signal levels occurring at lower frequencies. An example for A-13 is shown in Figure 2-2. Unfortunately, the background noise has been such as to render inconclusive the significance of particular peaks observed in the data. Analysis of the differences between signal and noise, and of signal/noise ratios, was also found to be inconclusive because of variabilities in the noise level. On the other hand, the general signal level (power spectral density) of the data was consistently greater than that of the noise. In some cases, this excess persisted over the frequency range 0-4 kHz that was covered in the analysis. In others, the excess existed at lower frequencies but disappeared at some point between 600 Hz and 1000 Hz. In one such case, the excess reappeared at about 3200 Hz.

Work is in progress to overcome the noise problem so that actual peaks can be discerned. When this is accomplished, tests will be performed

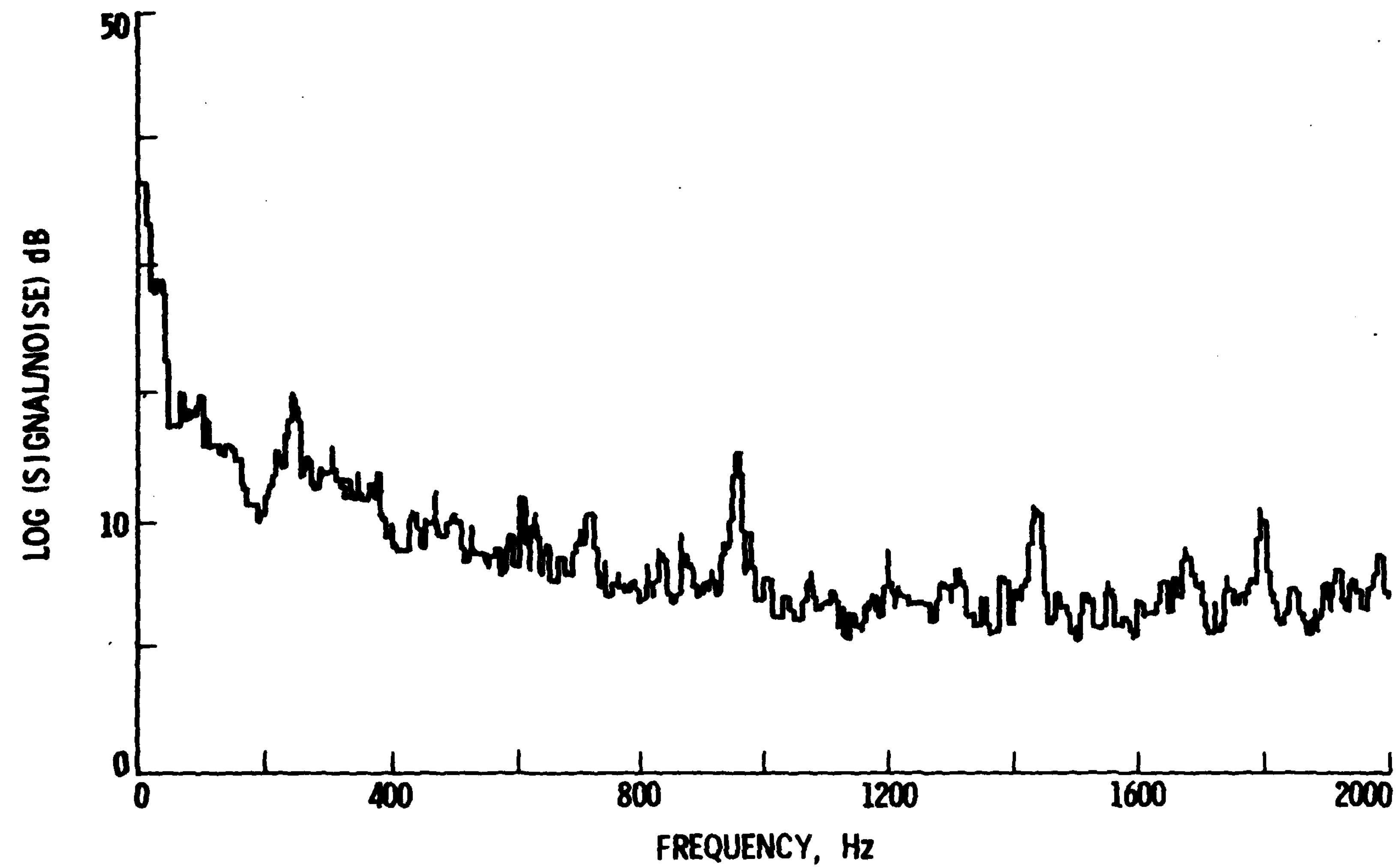

Figure 2-2. Spectral Content of Dynamic Burning Rate/Background Noise Ratio for A-13 at 2 MPa

with the same propellants undergoing EDAX/SEM studies.

2.2.3 Dynamic Burning Under Oscillatory Pressures: Response Function Data

Response function data are available for five propellants of interest, and data for a sixth propellant are in the process of being acquired. Future plans consist of acquiring data for approximately five additional selected propellants.

2.3 HIGH PRESSURE COMBUSTION EXPERIMENTS

Several HMX propellants were formulated and testing at pressures up to 1 kbar (100 MPa) was initiated. The testing was delayed by the need to return the base assembly of the high pressure closed vessel to the manufacturer to correct a manufacturing error uncovered during the initial testing. Testing has included formulations containing both fine and coarse HMX. In the case of fine HMX, nothing new or unusual was detected relative to observations made at 35 MPa in prior work. However, in the case of coarse HMX, cracked HMX particles were observed on the extinguished propellant surface for the first time. In the prior work (Ref. 15), evidence of cracking was carefully sought up to pressures of 35 MPa but none was found. The cracking could be significant to the high pressure combustion process.

Future plans consist of extending the test pressure incrementally to 7 kbar (700 MPa), and testing propellants containing AP and aluminum as well as HMX.

2.4 DDT MODEL

Discussions were held with SRI International for the purpose of integrating the JPL nitramine propellant transient combustion model into the SRI shock hydrodynamic model for DDT (Refs. 4 and 5). These two models complement each other because each contains mechanisms relevant to DDT which are not included in the other. The discussions consisted of a review and presentation of the models, how they would fit together from both a mechanistic standpoint and a procedural implementation standpoint, and speculation as to the significance of the combined model. Perhaps the most important point was the strong possibility that DDT could be achieved in a monolithic propellant grain without a granulated or shredded propellant. A number of analytical modeling attempts have tried to achieve this over the past 20 years, but have been unsuccessful because of simplifying assumptions or the neglect of important contributing mechanisms. It is of special significance because all Navy-sponsored work is based upon flawed propellant or the development of mechanical defects in propellants.

No actual progress was made toward combining the two models. It was left as a task to be led by SRI, with JPL assistance, whenever support would be forthcoming in the future.

SECTION 3

TECHNICAL JOURNAL PUBLICATIONS

The following publication appeared in the AIAA Journal during the past year:

(1) Cohen, N. S., "Response Function Theories That Account for Size Distribution Effects - A Review", AIAA J., Vol. 19, No. 7 (July 1981), pp. 907-912.

The following papers have been accepted for AIAA Journal publication:

(2) Strand, L. D. and Cohen, N. S., "Porous Plate Analog Burner Study of Composite Solid Propellant Flame Structure", AIAA J., Vol. 20, No. 4 (April 1982), pp. 569-570.

(3) Cohen, N. S. and Strand, L. D., "An Improved Model for the Combustion of AP Composite Propellants", presented as AIAA Paper 81-1553.

The following paper is being considered for AIAA Journal publication:

(4) Cohen, N. S., "A Pocket Model for Aluminum Agglomeration in Composite Propellants", presented as AIAA Paper 81-1585.

Chemical Propulsion Information Agency (CPIA) publications are listed in Subsection 5.1.

SECTION 4

PROFESSIONAL PERSONNEL

The Principal Investigator for this program is Leon D. Strand of the Thermochemical Research and Systems Section (M/S 122/123), Jet Propulsion Laboratory/California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109 (telephone 213-354-3108). His co-investigator is Dr. Norman S. Cohen, Cohen Professional Services, 141 Channing St., Redlands, California 92373 (telephone 714-792-8807).

Mr. Strand has overall program responsibility and specific responsibility for the experimental work performed. Dr. Cohen works under a subcontract, and is responsible for the analytical model developments. Both are former members of the AIAA Technical Committee on Propellants and Combustion. Mr. Strand is currently an associate editor of the "AIAA Journal of Spacecraft and Rockets", and Dr. Cohen is a member of the JANNAF Combustion Working Group.

SECTION 5

INTERACTIONS (COUPLING ACTIVITIES)

5.1 PRESENTATIONS

The following presentations have been made under this research contract:

(1) Cohen, N. S. and Strand, L. D., "A Model for the Burning Rates of Composite Propellants", 17th JANNAF Combustion Meeting (CPIA Publication 329, Vol. I, Nov. 1980), pp. 53-97.

(2) Cohen, N. S. and Strand, L. D., "Non-Steady Combustion of Composite Propellants", 1981 Joint AFOSR/AFRPL Rocket Propulsion Research Meeting, Lancaster, California (March 1981).

(3) Cohen, N. S. and Strand, L. D., "An Improved Model for the Combustion of AP Composite Propellants", AIAA Paper 81-1553, AIAA/SAE/ASME 17th Joint Propulsion Conference, Colorado Springs, Colorado (July 1981).

(4) Cohen, N. S., "A Pocket Model for Aluminum Agglomeration in Composite Propellants", AIAA Paper 81-1585, AIAA/SAE/ASME 17th Joint Propulsion Conference, Colorado Springs, Colorado (July 1981).

(5) Cohen, N. S. and Strand, L. D., "Effects of AP Size Distribution on the Pressure-Coupled Response Function", 18th JANNAF Combustion Meeting, Pasadena, California (October 1981); publication pending.

5.2 INTERCHANGE FUNCTIONS WITH GOVERNMENT LABORATORIES AND CONTRACTORS

The development of improved, high energy, low burn-rate propellants by Thiokol Corporation, and its culmination in the successful delivery of the highest specific impulse ever achieved for a solid rocket motor at the Arnold Engineering Division Center (AEDC) have been noted as 1981 highlights by the AIAA Technical Committees on Solid Rockets and Propellants & Combustion (Ref. 16). This is particularly gratifying because the analytical models developed during FY 1979-1980 in the course of this research were used in the optimization of those propellants for low burn-rate and favorable aluminum agglomeration. Discussions with Thiokol personnel (Dr. W. N. Brundige, Elkton Div. and W. O. Munson, Wasatch Div.) have continued regarding the achievement of even lower burn-rates without loss of performance efficiency. Those programs were sponsored by the Air Force Rocket Propulsion Laboratory (AFRPL) for upper-stage and space motor applications. Research information on the subject of aluminum behavior has also been exchanged with Professors E.W. Price, Georgia Institute of Technology, and J.R. Osborn, Purdue University.

Information derived from past research on the subject of nitramine propellant combustion was used to complement current efforts in progress at Thiokol Corporation (Dr. D.A. Flanigan, Huntsville Div.) under Air Force sponsorship and at Lockheed Missiles & Space Co. (Dr. G.A. Lo, Palo Alto Research Laboratory). Discussions were held with Stanford Research International (Dr. M. Cowperthwaite) on the details of combining their shock hydrodynamic model with the transient combustion model developed at JPL, which would result in an improved DDT model.

Productive interchanges have taken place on the effects of AP size distribution on combustion instability. There were consultations with Thiokol Corporation regarding several Air Force-sponsored rocket motor development programs (Drs. R.B. Kruse, Huntsville Div. and K. Wanlass, Wasatch Div.) in which changes in motor stability were associated with changes in size distribution. Further contacts have established instances where seemingly small changes in size distribution, or a change in method of AP grinding or preparation, caused a significant change in the instability (R.O. Hessler, Thiokol Corporation, Huntsville Div.; M.J. Ditore, Aerojet Tactical Systems; R.R. Miller, Hercules Inc., Allegany Ballistics Laboratory (ABL); Dr. T.P. Rudy, United Technologies Corporation, Chemical Systems Division (CSD)). Plans are being made to acquire propellant samples for use in future research. Seemingly strange response function results acquired by the recent JANNAF round-robin can be explained by size distribution effects, and further examples of multi-peaked response function curves are being reported by colleagues. Discussions with the Air Force Rocket Propulsion Laboratory (J.N. Levine and J. Baum) reveal that a multi-peaked response function curve has important implications for non-linear and velocity-coupled combustion instability. It is planned to maintain close contact with work in progress at AFRPL, Aerojet and CSD as our own research evolves into these areas.

REFERENCES

1. Cohen, N.S., "Response Function Theories That Account for Size Distribution Effects - A. Review", AIAA J., Vol. 19, No. 7 (July 1981), pp. 907-912.

2. Andrepont, W.C., "An Assessment of Combustion Instability Technology for Solid Motors", 18th JANNAF Combustion Meeting, Pasadena, California (Oct. 1981), CPIA publication pending.

3. Strand, L.D., Magiawala, K.R. and McNamara, R.P., "Microwave Measurement of the Solid Propellant Pressure-Coupled Response Function", J. Spacecraft and Rockets, Vol. 17 (Dec. 1980), pp. 483-488.

4. Cowperthwaite, M., "Phenomenology in the Deflagration to Detonation Transition in Propellants and Explosives", 8th Detonation Symposium, Annapolis, Md. (July 1981).

5. Cohen, N.S., and Strand, L.D., "Transient Processes in the Combustion of Nitramine Propellants", AFOSR-TR-79-0244, Jet Propulsion Laboratory, Pasadena, California (Nov. 1978).

6. Culick, F.E.C., "Calculation of the Admittance Function for a Burning Surface", Astronautic Acta, Vol. 13 (1967), pp. 221-237.

7. Eisel, J.L., Ryan, N.W. and Baer, A.D., "Combustion of $NH_4C\ell O_4$-Polyurethane Propellants: Pressure, Temperature and Gas Phase Composition Fluctuations", AIAA J., Vol. 12, No. 12 (Dec. 1972), pp. 1655-1661.

8. Ilyukhin, V.S. et al., "Role of Heterogeneity of Composite Solid Fuels in the Mechanism of Pulsation Burning", Fizika Goreniya i Vzryva, Vol. 11, No. 3 (1975), pp. 498-501.

9. Strahle, W.C. and Handley, J.C., "Prediction of Combustion-Induced Vibration in Rocket Motors", Final Report, Contract DASG-60-77-C-0054, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia (April 1978).

10. Beckstead, M.W., Derr, R.L. and Price, C.F., "A Model of Solid Propellant Combustion Based on Multiple Flames", AIAA J., Vol. 8, No. 12 (Dec. 1970), pp. 2200-2207.

11. Hamann, R.J., "Three Solid Propellant Combustion Models, A Comparison and Some Application of Non-Steady Cases", Memo, M-215, Delft University of Technology, Delft, Netherlands (April 1974).

12. Novozhilov, B.V., "Nonstationary Combustion of Solid Rocket Fuels", translation FTD-MT-24-317-74, Wright-Patterson AFB, Ohio (Sept. 1973).

13. Condon, J.A., Osborn, J.R. and Glick, R.L., "Statistical Analysis of Polydisperse, Heterogeneous Propellant Combustion: Nonsteady-State", 13th JANNAF Combustion Meeting (CPIA Publication 281, Vol. II, 1976) pp. 209-223.

14. Cohen, N.S. and Strand, L.D., "An Improved Model for the Combustion of AP Composite Propellants", AIAA Paper 81-1553, AIAA/SAE/ASME 17th Joint Propulsion Conference, Colorado Springs, Colo. (July 1981).

15. Cohen, N.S. and Strand, L.D., "Nitramine Propellant Research", Report AFOSR-TR-76-1163, Jet Propulsion Laboratory, Pasadena, California (July 1977).

16. Aeronautics and Astronautics, 1981 Highlights Issue (American Institute of Aeronautics and Astronautics publication, New York, NY, Dec. 1981), pp. 75, 81.

ABBREVIATIONS AND ACRONYMS

ABL	Allegany Ballistics Laboratory
AEDC	Arnold Engineering Division Center
AFRPL	Air Force Rocket Propulsion Laboratory
AP	ammonium perchlorate
CPIA	Chemical Propulsion Information Agency
CSD	Chemical Systems Division
DDT	deflagration-detonation transition
EDAX	energy dispersive analysis of x-rays
JANNAF	Joint Army Navy NASA Air Force
SEM	scanning electron microscope
SRI	*Stanford Research Institute*